GEOLOGY | THE GEOLOGICAL SOCIETY OF AMERICA®

https://doi.org/10.1130/G51965.1

Manuscript received 10 December 2023
Revised manuscript received 11 May 2024
Manuscript accepted 5 July 2024

Published online XX Month 2024

The construction of the Giza pyramids chronicled by human copper contamination

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ABSTRACT

Although the construction of the Giza necropolis necessitated the creation of an extensive array of metal tools, the significance of these early instances of metallurgy, and the contamination they left, has been overlooked in favor of understanding pyramid building techniques. We geochemically analyzed a sediment core from the Khufu harbor, on the Nile floodplain at Giza, Egypt, to track the construction of the necropolis, with a particular focus on copper contamination deriving from metallurgical activities. We found that significant local contamination occurred during the regnal years of Kings Khufu, Khafre, and Menkaure, consistent with metalworking during the preparation and construction of the edifices. While the pyramid complex led to the creation of an outstanding cultural legacy for humanity, it also marked the onset of significant human-caused metal contamination at Giza.

INTRODUCTION

The pyramids of Giza, one of the world's most iconic cultural landscapes, are monumental edifices that served as the final resting place for kings of the Old Kingdom's Fourth Dynasty (Lehner and Hawass, 2017; Verner, 2021). The Great Pyramid of Giza, an architectural marvel constructed under the reign of King Khufu (first regnal year: 2613–2577 BCE; Bronk Ramsey et al., 2010), stands as an enduring testament to human ingenuity and holds a well-deserved place among the Seven Wonders of the Ancient World. The second edifice was built by King Khafre (first regnal year: 2586–2548 BCE; Bronk Ramsey et al., 2010), and the final pyramid was erected by King Menkaure (first regnal year: 2564–2524 BCE; Bronk Ramsey et al., 2010). King Khufu reigned for 26–30 years (Gautschy et al., 2017; Jüngling and Höflmayer, 2023), and it has been estimated that the Great Pyramid was nearly completed during his reign. According to the journal of inspector Merer, at the end of King Khufu's reign, the white limestone blocks for cladding his pyramid were still brought from Tura (Tallet and Lehner, 2022). The building of the Great Pyramid, which required a massive workforce and support services such as scribes, stonemasons, metalworkers, carpenters, and foremen, is partly detailed in the Wadi al-Jarf papyri (Tallet, 2021). The population necessary to complete the project on-site probably ranged from 7,000 to 20,000 people (Smil, 2020).

The construction activities carried out on the Giza plateau must have resulted in a significant increase in contamination, particularly due to the widespread production and utilization of metallic tools (Odler et al., 2016; Odler and Kmošek, 2019; Odler et al., 2021). Archaeological artifacts reveal that craftsmen used copper tools for various tasks (work on limestone, textile, wood), sometimes alloying copper with arsenic to improve their properties, particularly hardness (Rademakers et al., 2020). Despite decades of research and archaeological discoveries, geochemical tracers have never been used at Giza to probe the site's long metallurgical history before, during, and after the Old Kingdom, notably during the Naqada period. While acknowledging potential limitations, particularly regarding the spatial extent and intensity of metalworking activities at Giza, utilizing the evolution of contaminants is a valuable method for reconstructing the local production of metal tools over thousands of years and encompassing various archaeological time periods.

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CITATION: Younes, G., et al., 2024, The construction of the Giza pyramids chronicled by human copper contamination: Geology, v. XX, p. XXX–XXX, https://doi.org/10.1130/G51965.1

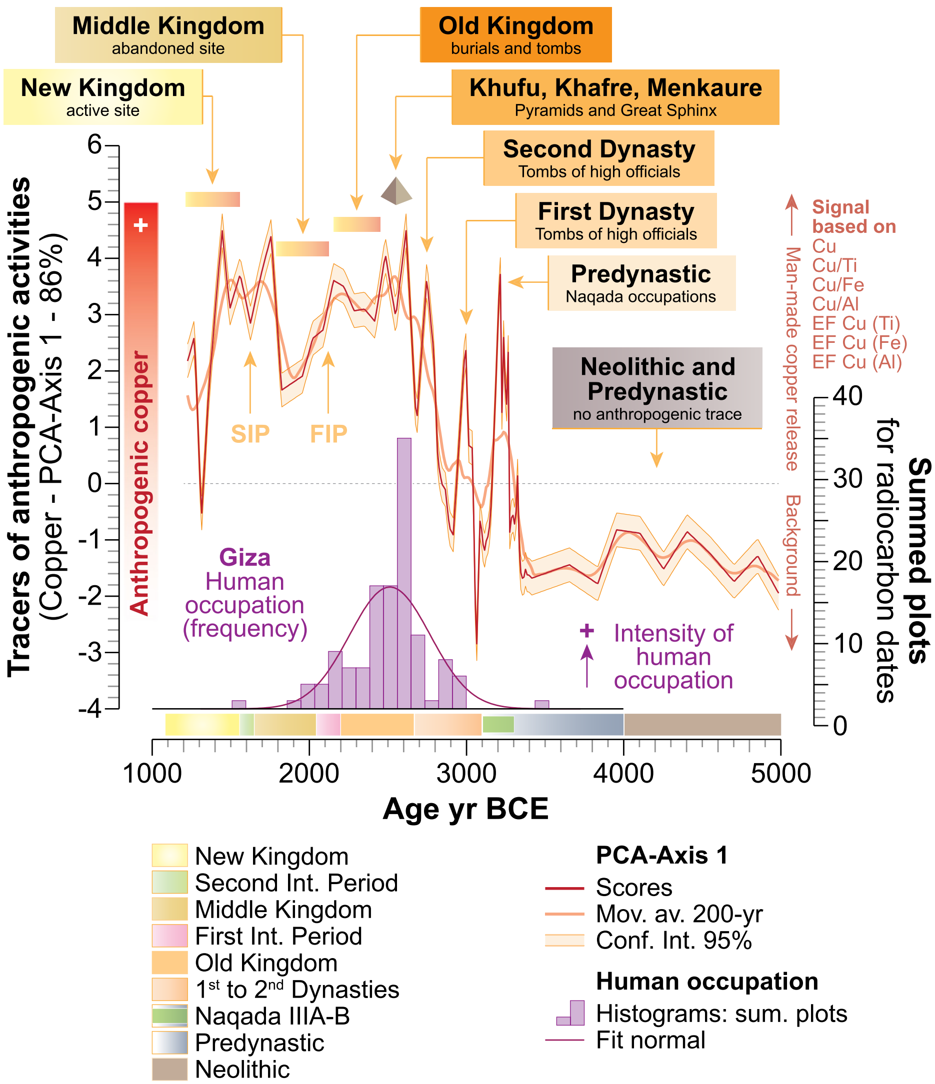

Figure 1. Metallurgy and human-made copper contamination at Giza from the Copper Age to the New Kingdom. Copper contamination is shown as PCA-Axis 1 scores (with a 200-year moving average [Mov. av.] and a 95% confidence interval [Conf. Int.]) and compared with the intensity of human occupation on the plateau (Lucarini et al., 2020). The primary periods of contamination align closely with attested historical events. The First Intermediate (Int.) Period (FIP) and Second Intermediate Period (SIP) are marked with an arrow. sum[illegible]mmed.

METHODS

We reconstructed copper contamination in the Giza area (Figs. S1 and S2 in the Supplemental Material[1]) from the Neolithic to the New Kingdom, spanning ~3200 yr (6465 ± 80 to 1225 ± 80 BCE). This record is based on sediments from the Khufu harbor (core GIZA 3; Younes et al., 2024), which was overlooked by the pyramid complex (Lehner, 2020). Preserved in a refrigerated container, the core underwent sediment subsampling for geochemical analyses. Sediments were digested and analyzed for copper (Cu), aluminum (Al), iron (Fe), titanium (Ti), and arsenic (As) using an inductively coupled plasma–mass spectrometry (ICP-MS) quadrupole Perkin Elmer Nexlon 300X. Copper concentrations, expressed in ppm, were evaluated against refractory crustal elements (CE) ratios, defining an enrichment factor (EF). The EF revealed anthropogenic copper contamination, notably from the onset of Cu use in the Nile valley. The reconstruction of copper contamination coupled with arsenic (Figs. S3a–S3b), using z-scores, PCA (principal component analysis; Fig. S4), and chronological interpolation provides a detailed picture of metalworking activities and their environmental impact across millennia. The laboratory methods are detailed in the Supplemental Material.

[1]Supplemental Material. Figures S1 to S5 and Datasets S1 to S7. Please visit https://doi.org/10.1130/GEOL.S.XXXX to access the supplemental material; contact editing@geosociety.org with any questions.

RESULTS AND DISCUSSION

Naqada IIIA-IIIB Occupation

The Predynastic rise in copper contaminants (−0.86[illegible]6; Figs. 1, 2A, and 2B) and arsenic (up[illegible].4 ppm; Fig. S3), from 3265 ± 80 to 3185 ± 80 BCE, appears consistent with a Naqada IIIA-IIIB occupation (Dee et al., 2013) of the Giza plateau, also supported by an early intensification in local agropastoral activities (Fig. 2B; Sheisha et al., 2023). The sharp increase in metallurgy and copper contamination (score of 3.26; Fig. 1), providing evidence of local metalworking during this period, is a compelling indication of late Predynastic activity at the site, which is, however, absent from current archaeological records. The only confirmed late Predynastic remains in the area are 13 graves from the small family cemetery of Kafr Ghattati north of Giza (Engles, 1990), with the beginning attributed to Naqada IIIB (Hendrickx and Brink, 2002). Local settlements, if present, were probably destroyed when the Fourth Dynasty pyramids were erected. There was probably a Naqada population practicing metallurgy at Giza, predating evidence from the Memphite region. Inscriptions (Tallet and Laisney, 2013) also attest to mining expeditions and the use of copper from the Naqada III culture (Hauptmann, 2007). The elevated peak of arsenic observed during this period (Fig. S3) could potentially be linked to its use in alloying with copper, given that arsenic has been detected in Egyptian metalwork since at least the Naqada II period. A high contamination (Fig. S3) probably means less control over the arsenic in the metalworking compared to the Dynastic period. However, with the exception of Maadi, scant information exists regarding Predynastic metalworking workshops (Odler, 2023).

First Dynasty of Egypt

The second notable increase, observed as a shift from 3035 ± 80 to 2945 ± 80 BCE (−0.5[illegible]20; Fig. 1), is believed to be associated [illegible]h the construction of tombs on the Giza plateau. This period coincided with the final phase of high-water levels in the Khufu branch of the Nile (Figs. 2A and S5a). This period likely represents a significant phase in the construction of Early Dynastic monuments, particularly on those sites that would eventually form the pyramid fields. At Giza, anything below the Old Kingdom pyramid and tomb complexes would have been largely destroyed, but Early Dynastic tombs, ranging from the First to the Third Dynasties have been uncovered in the southern part of the Giza necropolis (Martin, 1997). The peaks in copper contamination with arsenic up to 5.9 ppm (Fig. S3), attributed to the First Dynasty, are most probably connected to the construction of tombs of high officials at Giza and in its vicinity. Copper contamination places the early stage of funeral constructions at

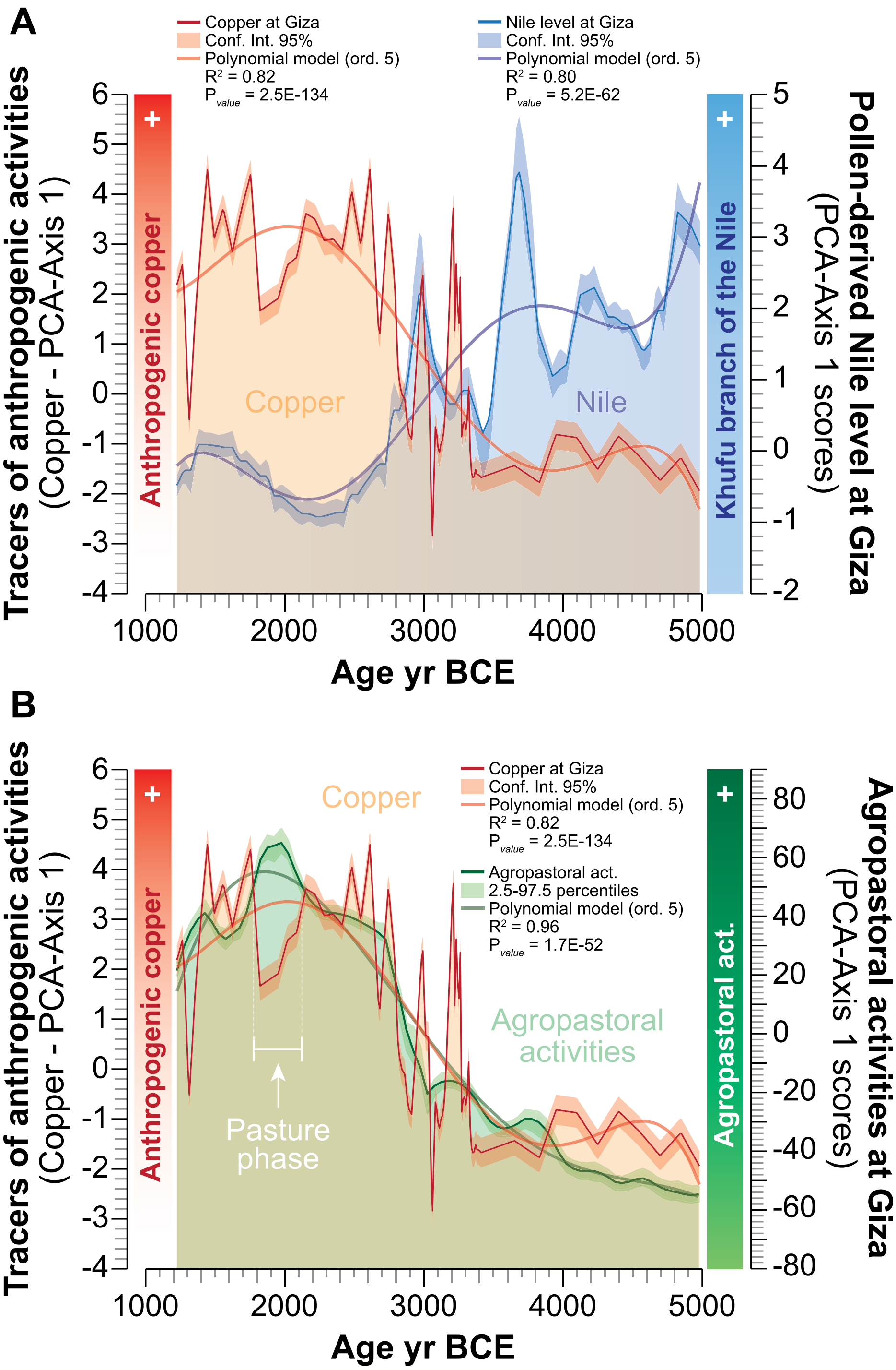

Figure 2. Copper contamination compared with the Nile level and agropastoral activities (act.) at Giza. Copper contamination, shown as PCA-Axis 1 scores, is compared with (A) the level of the Khufu branch of the Nile (Sheisha et al., 2022) and (B) the evolution of agropastoral activities on the Giza plateau (Sheisha et al., 2023). Conf. Int.—confidence interval.

3035 ± 80 BCE, providing new chronological evidence, based on geochemistry, that complements and reinforces the archaeological record.

Second Dynasty

A significant increase in copper contamination occurred between 2795 ± 80 and 2715 ± 80 BCE, during the Second or Third Dynasty (see Fig. 1). Archaeological findings at Giza have uncovered tombs of prominent officials from both the Second and Third Dynasties (Martin, 1997), hindering further refinement regarding the specific origin of the copper and arsenic contamination although a Second Dynasty attribution is most likely based on current ^{14}C chronologies. This episode coincides with both a major drop in the Khufu branch level (Figs. 2A and S5a) and a strong development in agropastoral activities (Figs. 2B and S5b). At Giza, evidence of metalworking abruptly declined around 2715 ± 80 BCE, suggesting a partial abandonment of metallurgy on the plateau until the reign of King Djoser. This suggests that socioeconomic parameters before the Third Dynasty influenced local human behavior.

The Giza Pyramid Complex

The first major phase of copper contamination, with more control on arsenic in metalworking (average of 2.5 ± 0.1 ppm), dates from 2615 ± 80 to 2485 ± 80 BCE (1.2–4.[illegible]; Fig. 1), a chronological range that corresponds to the construction of the Giza necropolis. The building of the Great Pyramid has been previously dated either indirectly by the accession date of King Khufu and the length of his reign or directly by astronomical observations. The proposed chronology extends from 2636 to 2606 BCE (Gautschy et al., 2017; Tallet and Lehner, 2022) to 2480 ± 5 BCE (Spence, 2000), including several possibilities such as 2613–2577 BCE (Bronk Ramsey et al., 2010), 2589 BCE (Shaw, 2000), 2554 BCE (von Beckerath, 1997), and 2509 BCE (Hornung et al., 2006). A completion date for the Great Pyramid has also been estimated at 2559–2518 BCE (Dee et al., 2009). Copper contamination dates the onset of massive metalworking on the Giza plateau to 2615 ± 80 BCE, a date supporting the hypothesis of an extensive occupation of Giza and edifice construction beginning in the late twenty-seventh century or early twenty-sixth century BCE. The discernible increase in contamination levels at Giza is coherent with significant copper-tool findings, including chisels, needles, axe blades, clamps/nails, and awls that have been discovered and identified as artifacts utilized in the construction of the Khufu and Khafre edifices and related projects (pyramids and the Great Sphinx; Odler et al., 2021). Copper contamination moderately declines at 2545 ± 80 BCE (Fig. 1), which may correspond to the reign of King Djedefre, who built his pyramid at Abu Roash, not on the Giza plateau (Gautschy et al., 2017). Completion dates have been estimated for the Pyramids of King Khafre (2527–2463 BCE) and King Menkaure (2456–2370 BCE; Dee et al., 2009). The second increase in copper contamination is centered on 2485 ± 80 BCE (from 2545 ± 80 to 2415 ± 80 BCE; Fig. 1), in line with the length of the reigns of King Khafre and King Menkaure (24 and 19 years, respectively; Gautschy et al., 2017). Metallurgy on the Giza plateau did not stop after the construction of the pyramids, and the site remained active throughout the Old Kingdom, with numerous tombs attributed to royal officials of high, middle, and low rank (Porter et al., 1994; Odler et al., 2016) (Fig. 3). A sharp decline in metalworking, however, was recorded after 2155 ± 80 BCE (Fig. 1) at the

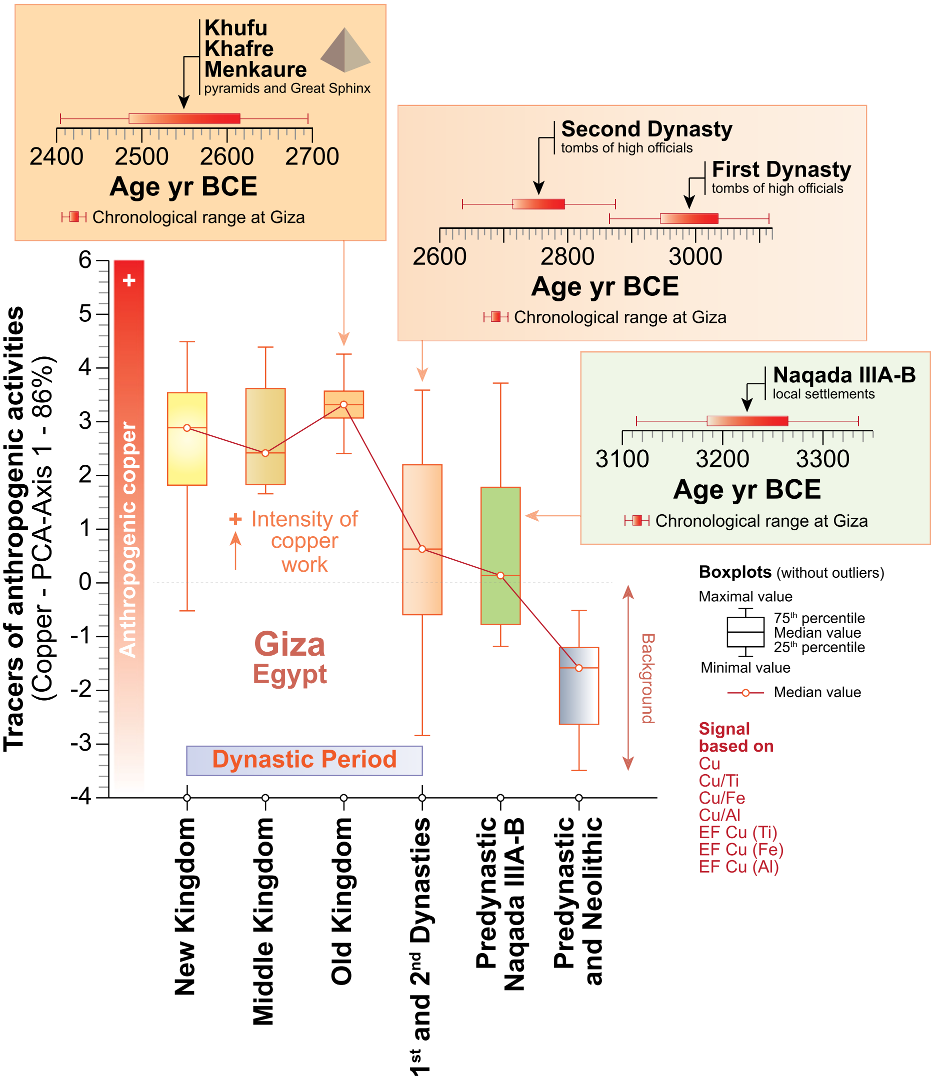

Figure 3. Evolution of copper contamination by archaeological/historical period. Boxplots showing the evolution of copper contamination from the Neolithic to the New Kingdom. The phases of increased copper contamination from the Predynastic Period to the Old Kingdom are indicated as calibrated ^{14}C dates (with the associated 2σ–95% probability) plotted in relation to major archaeological events at Giza.

onset of the First Intermediate Period (ca. 2150 BCE; Seidlmayer, 2000).

First Intermediate Period and Middle Kingdom

During the First Intermediate Period, the Giza plateau went through a phase of abandonment of the building area and copper metallurgy, followed by a prolonged period of decline throughout a significant portion of the Middle Kingdom (Zivie-Coche, 1976). However, the presence of a few known artifacts from these periods offers compelling evidence in support of minor tombs in the area (Zivie-Coche, 1976). During the Twelfth Dynasty, the pyramids and tombs were plundered, while the causeways and temples were repurposed as quarries by pharaohs for their own building projects (Zivie-Coche, 1976; Gilli, 2009). During this period, traces of copper working weaken at Giza (3.6[illegible] Fig. 1), with an overall drop in contamin[illegible] throughout the Eleventh and Twelfth Dynasties (Fig. 3). The remaining activity on the plateau (Fig. 1) probably resulted from workers removing stone from the Giza necropolis. A significant decline in agriculture and an extension of grazing has also been elucidated on the floodplain surrounding the harbor (Fig. 2B; Sheisha et al., 2023). However, a revival of copper metallurgy occurred after 1755 ± 80 BCE, during the Thirteenth Dynasty, probably during the reign of King Sobekhotep I (first regnal year: 1777–1712 BCE; Bronk Ramsey et al., 2010) or his successors. This activity is clearly identified by metal contamination and probably corresponds to a limited occupation of the Giza plateau. These limited constructions in the area are recorded by rare archaeological artifacts (Zivie-Coche, 1976). Following the decline of the Middle Kingdom and the onset of the Second Intermediate Period, there was a notable decrease in contaminants at Giza (4.4–2.85; Fig. 1). This downturn suggests a decrease in metallurgical activity in the pyramids field.

New Kingdom

Around 1565 ± 80 BCE and the onset of the New Kingdom and the reign of King Ahmose (first regnal year: 1566–1552 BCE; Bronk Ramsey et al., 2010), Giza remained an active site and copper-arsenic contamination from the plateau rose again (2.85[illegible]5; Fig. 1). The higher peak was attained [illegible]45 ± 80 BCE (4.5; Fig. 1), most probably during the regnal years of king Amenhotep II (first regnal year: 1441–1431 BCE; Bronk Ramsey et al., 2010) who built the Temple of Hauron-Haremakhet to the northeast of the Sphinx, and erected a stela (Pasquali, 2009; Bassir, 2017). A chapel may have been built before by King Thutmose I (first regnal year: 1520–1507 BCE; Bronk Ramsey et al., 2010) but its origin remains unclear (Porter et al., 1994). Copper contamination remained high during the reign of King Thutmose IV (first regnal year: 1414–1403 BCE; Bronk Ramsey et al., 2010), who erected the "Dream Stela" and built an enclosure wall around the Sphinx to protect the statue (Zivie-Coche, 1976; Bassir, 2017). During the reign of King Tutankhamun (first regnal year: 1349–1338 BCE; Bronk Ramsey et al., 2010), a structure now referred to as the king's resthouse was built (Porter et al., 1994). King Seti I (first regnal year: 1307–1296 BCE; Bronk Ramsey et al., 2010) made additions to the Temple of Hauron-Haremakhet (Porter et al., 1994). A significant resurgence in contamination levels, marked by a sharp rise following a period of decline centered on 1315 ± 80 BCE (−0.5; Fig. 1), occurred during the reign of Ramesses II (first regnal year: 1292–1281 BCE; Bronk Ramsey et al., 2010), who erected a stela and usurped the king's resthouse (Porter et al., 1994).

CONCLUSIONS

The geochemical analysis of sediments from Khufu harbor has unveiled a rich history of Predynastic and Dynastic Egypt on the Giza plateau and its vicinity, highlighted by metallurgical evidence and copper contamination (Fig. 1). This analysis also pinpointed a Predynastic Naqada occupation within the area. These new findings provide valuable insights for future research on the plateau, especially regarding the Predynastic period. The contamination record also shows that the development of Giza as a necropolis was directly influenced by a drop in Nile levels (Fig. 2A). The historical tapestry of Giza reveals that the plateau was shaped by a multitude of communities, including ancient traces of agropastoralism (Fig. 2B). However, the most conspicuous imprint is undoubtedly the pervasive metallic contamination that originated from extensive metalworking activities associated with the construction of the necropolis, subsequent looting, and the addition or renovation of later buildings (Fig. 3). The construction of the pyramid complex was a crowning achievement of the ingenuity and ambition of Dynastic Egypt. However, it is essential to acknowledge that this monumental endeavor also left an indelible mark on the Giza plateau in the form of the first major human-caused metal contamination.

ACKNOWLEDGMENTS

Drilling permission was obtained with the help of the National Research Institute of Astronomy and Geophysics (NRIAG, Helwan, Egypt). Financial support was provided by: Centre de recherche et d'enseignement des géosciences de l'environnement (CEREGE) laboratory (APIC Research project), Mission pour les Initiatives Transverses et Interdisciplinaires–Centre national de la recherche scientifique (MITI-CNRS; AQUASANMARCO project), ARKAIA Institute (Institute of Mediterranean Archaeology; GIZA project), National Natural Science Foundation of China (grant no. 42106161 and grant no. 42261144741) and Maison des sciences de l'homme et de l'environnement (MSHE)–Université de Franche-Comté (GIZAPORT Project).

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Printed in the USA